PSF Estimation & Atmospheric Effects

Aaron Roodman
Kavli Institute for Particle Astrophysics & Cosmology
SLAC National Accelerator Laboratory

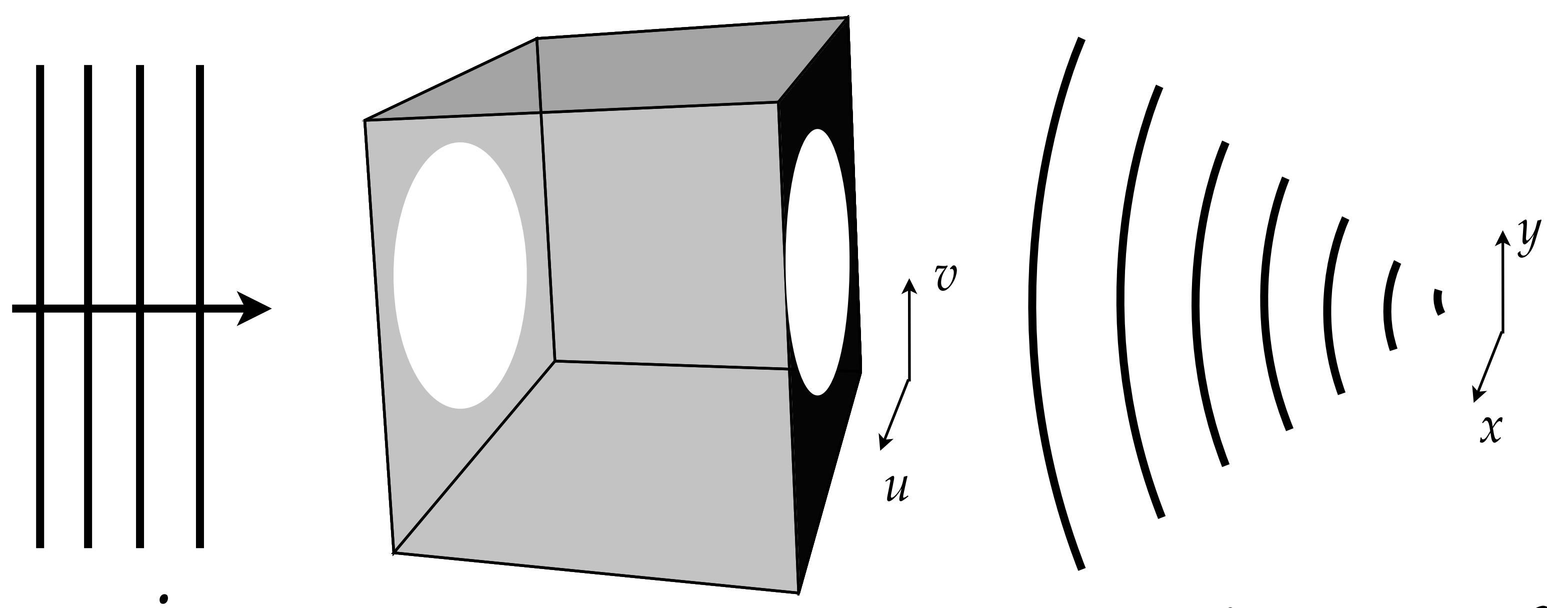
Impact of the Last Kiloparsec
UC Davis
Dec. 14 2015

Primer on Fourier Optics

a Telescope:

converts Angle on the Sky to Position on the Focal Plane

Idealized Telescope



incoming plane wave

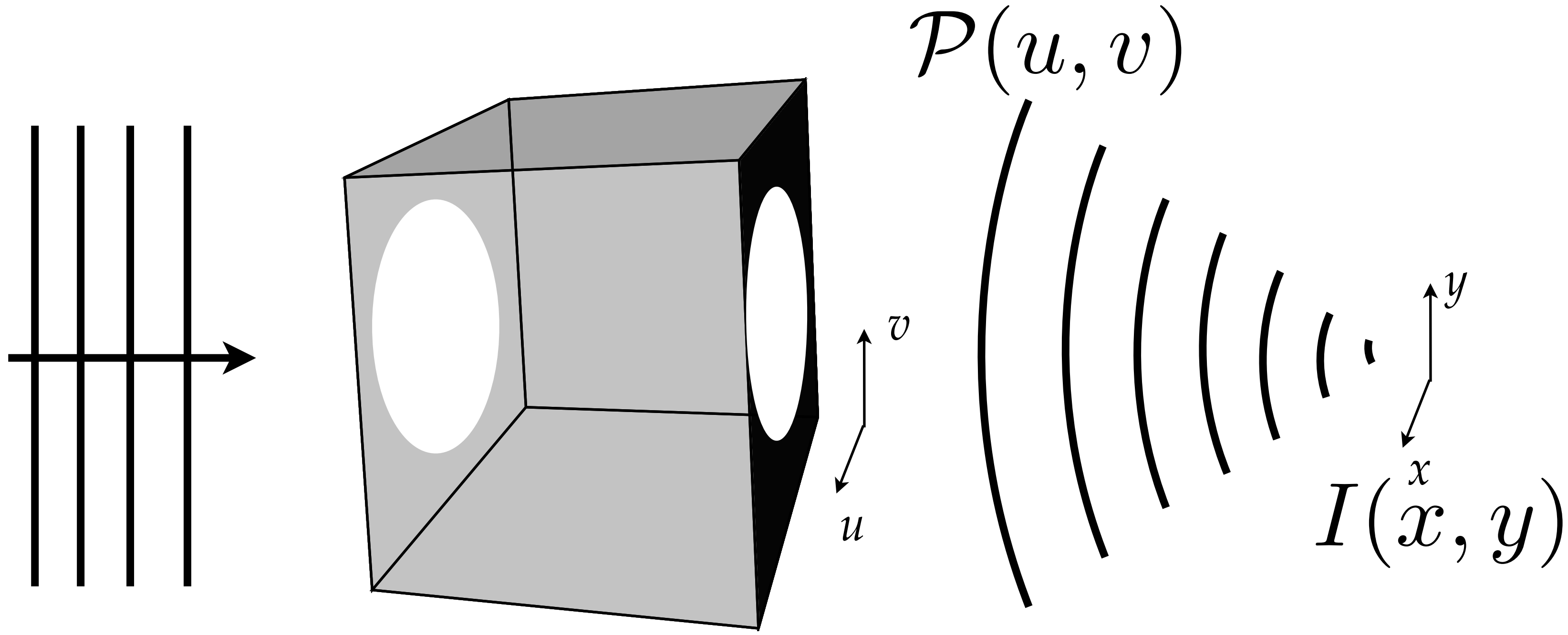
entrance, exit pupils

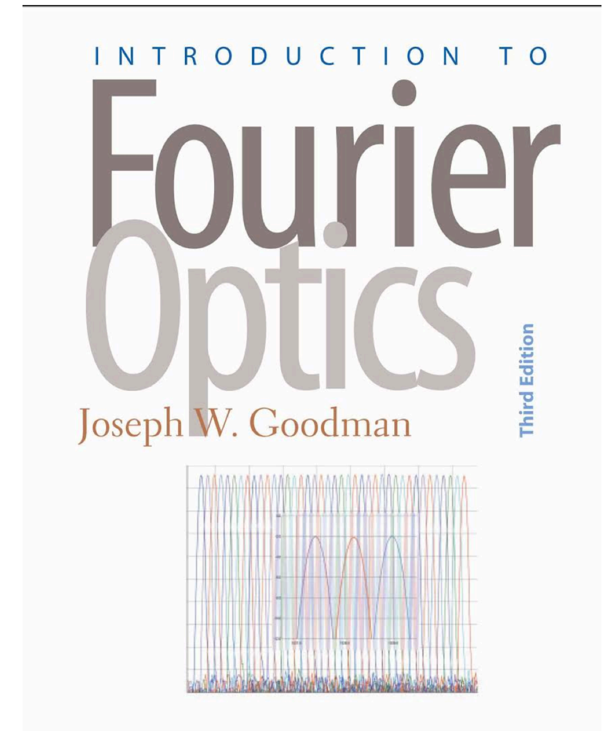
outgoing converging spherical wave

focal plane

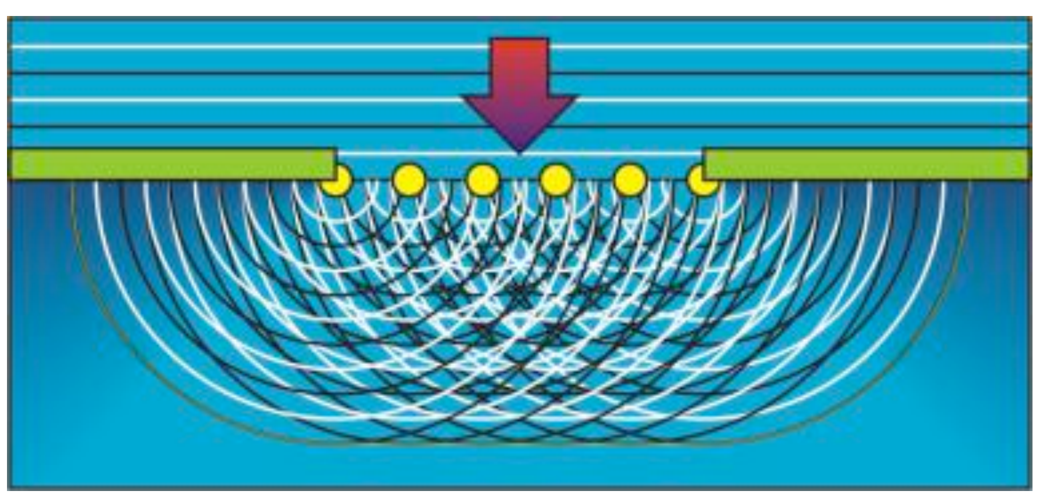
Angle & Position are Conjugate Variables

Fresnel Diffraction





$$I(x,y) = \left| \frac{1}{\lambda z} \int \left\{ \mathcal{P}(u,v) e^{i \frac{k}{2z}(u^2+v^2)} \right\} e^{-i \frac{2\pi}{\lambda z}(xu+yv)} du dv \right|^2$$



Huygens Principle

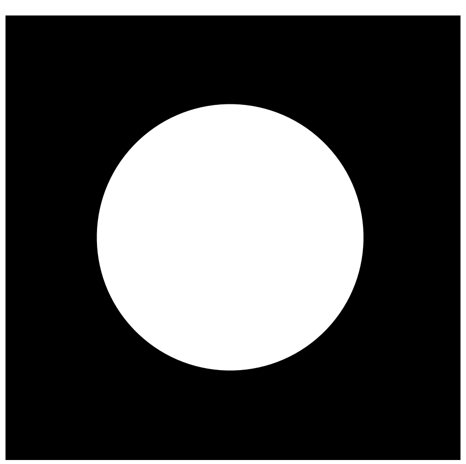
Fraunhofer Diffraction

Fresnel ⇨ Fraunhofer

- far field
- spherically converging beam

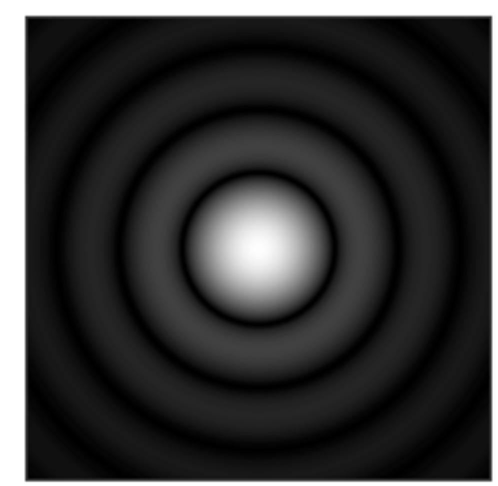
$$I(x,y) = \left| \frac{1}{\lambda z} \int \mathcal{P}(u,v) e^{-i\frac{2\pi}{\lambda z}(xu+yv)} dudv \right|^2$$

note that this is a Fourier Transform



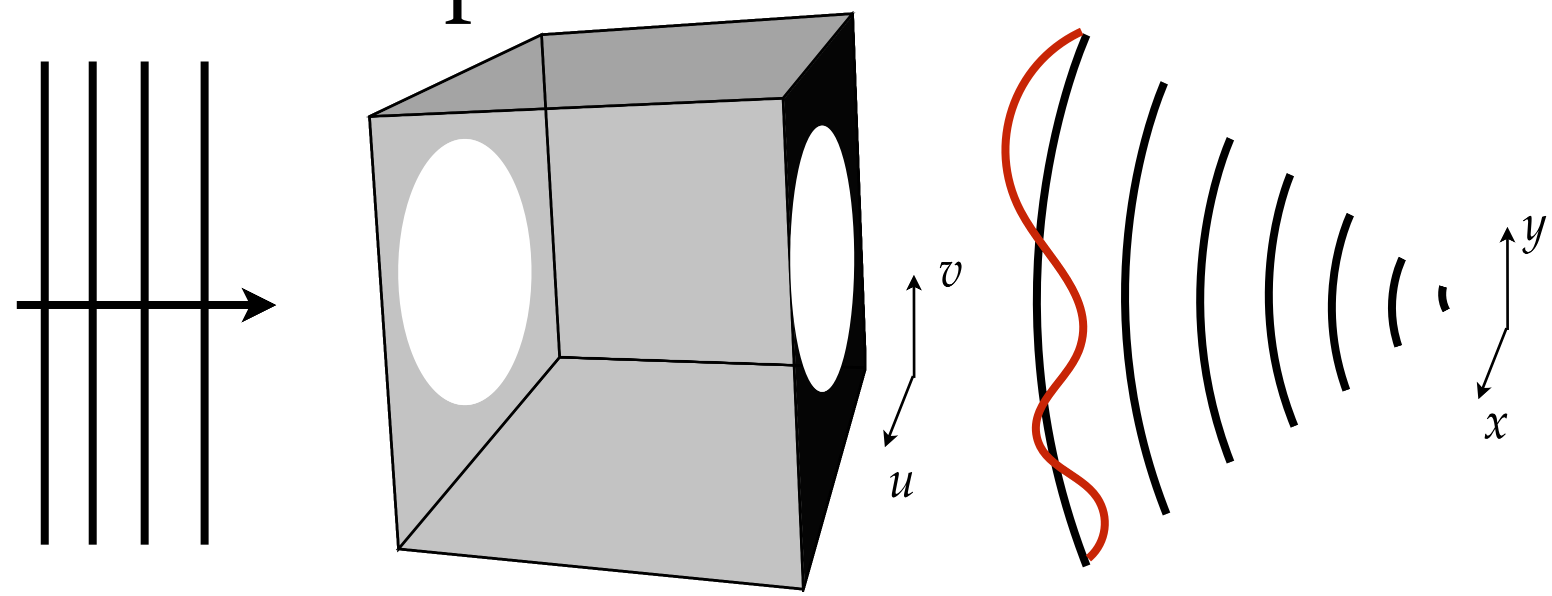
$\mathcal{P}(u,v)$ is the Pupil Function

Circular pupil and perfectly converging beam gives the Airy pattern

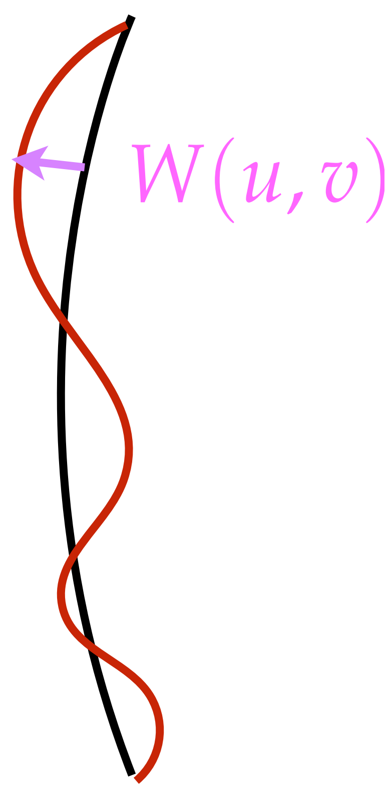


Wavefront & Zernike expansion

Imperfect optical system?



$$I(x,y) = \left| \frac{1}{\lambda z} \int P(u,v) e^{i 2\pi W(u,v)/\lambda} \, e^{-i \frac{2\pi}{\lambda z}(xu+yv)} du dv \right|^2$$



Wavefront or
Aberration Function

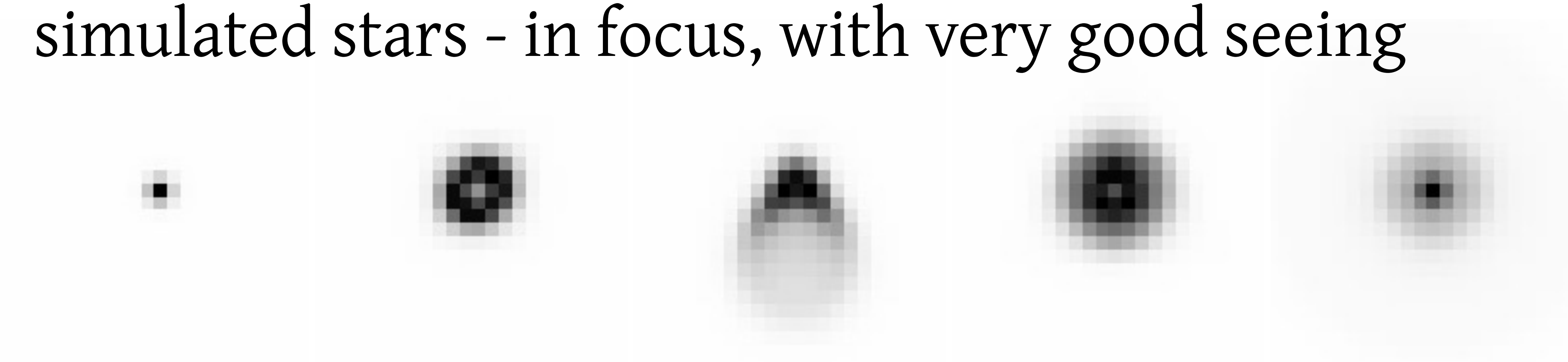
$$W(u,v) = \sum a_i Z_i(\rho,\theta)$$

Zernike expansion

Index	Name	Zernike Polynomial
2	Tilt X	$2\rho\cos\theta$
3	Tilt Y	$2\rho\sin\theta$
4	Focus	$\sqrt{3}(2\rho^2 - 1)$
5	Astigmatism Y	$\sqrt{6}\rho^2 \sin 2\theta$
6	Astigmatism X	$\sqrt{6}\rho^2 \cos 2\theta$
7	Coma Y	$\sqrt{8}(3\rho^3 - 2\rho)\sin\theta$
8	Coma X	$\sqrt{8}(3\rho^3 - 2\rho)\cos\theta$
9	Trefoil Y	$\sqrt{8}\rho^3 \sin 3\theta$
10	Trefoil X	$\sqrt{8}\rho^3 \cos 3\theta$
11	Spherical	$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$

Gallery of Aberrations

simulated stars - in focus, with very good seeing



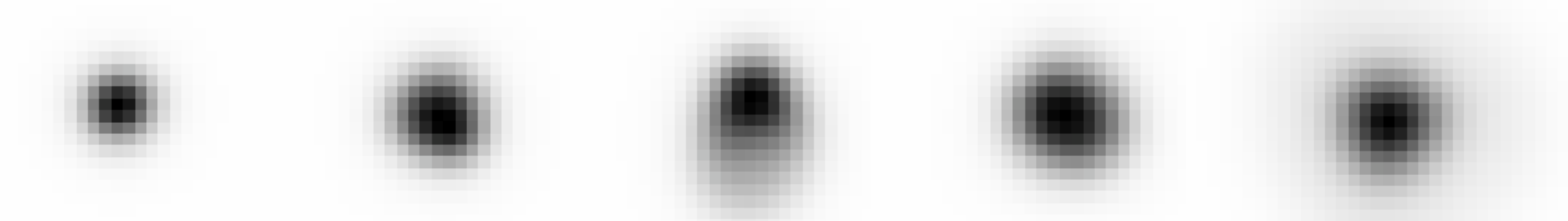
nominal 2λ Astigmatism 2λ Coma 2λ Trefoil 2λ Spherical

simulated stars - 1.5mm out of focus, with very good seeing

nominal 2λ Astigmatism 2λ Coma 2λ Trefoil 2λ Spherical

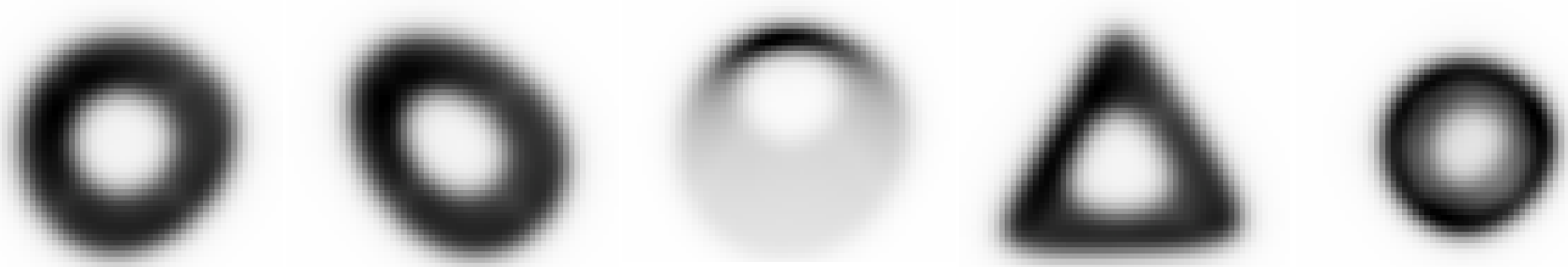
Gallery of Aberrations

simulated stars - in focus, with typical seeing



nominal   2λ Astigmatism   2λ Coma   2λ Trefoil   2λ Spherical

simulated stars - 1.5mm out of focus, with typical seeing



nominal   2λ Astigmatism   2λ Coma   2λ Trefoil   2λ Spherical

Donuts

PSF Contributions

$$I(x,y) = \sum_{t_i} \left| \mathcal{F}\left\{ P(u,v) e^{i2\pi W_i(u,v)/\lambda} \right\} \right|^2 \otimes \mathrm{CCD}(x,y|x',y')$$

$$W(u,v) = W_{\mathrm{optics}(u,v)} + W_{\mathrm{atmos.}(u,v)}$$

approximate as:

$$I(x,y) = \left| \mathcal{F}\left\{ P(u,v) e^{i2\pi W_{\mathrm{optics}}(u,v)/\lambda} \right\} \right|^2 \otimes \mathrm{Seeing} \otimes \mathrm{CCD}$$

LSST FWHM Requirements: 0.25" 0.6" 0.3"

Sources of Ellipticity:
may be roughly equal parts optics & seeing

CCD Brighter-Fatter effect violates convolution

PSF Estimation from Optical Wavefronts

PSF usually measured in Stars
and *interpolated* to location of Galaxies

instead Estimate PSF from knowledge of Optical system
advantages:

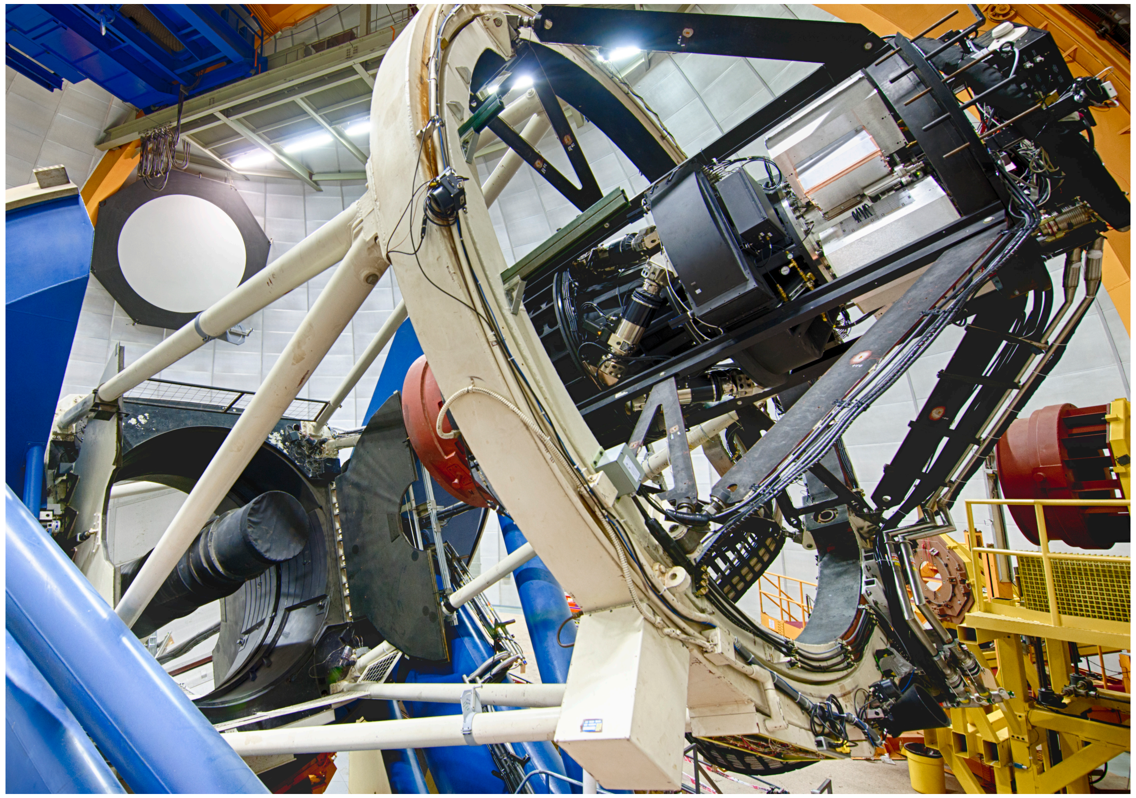
- requires far fewer free parameters
- uses knowledge of system behavior
- potential to improve quality of PSF estimates

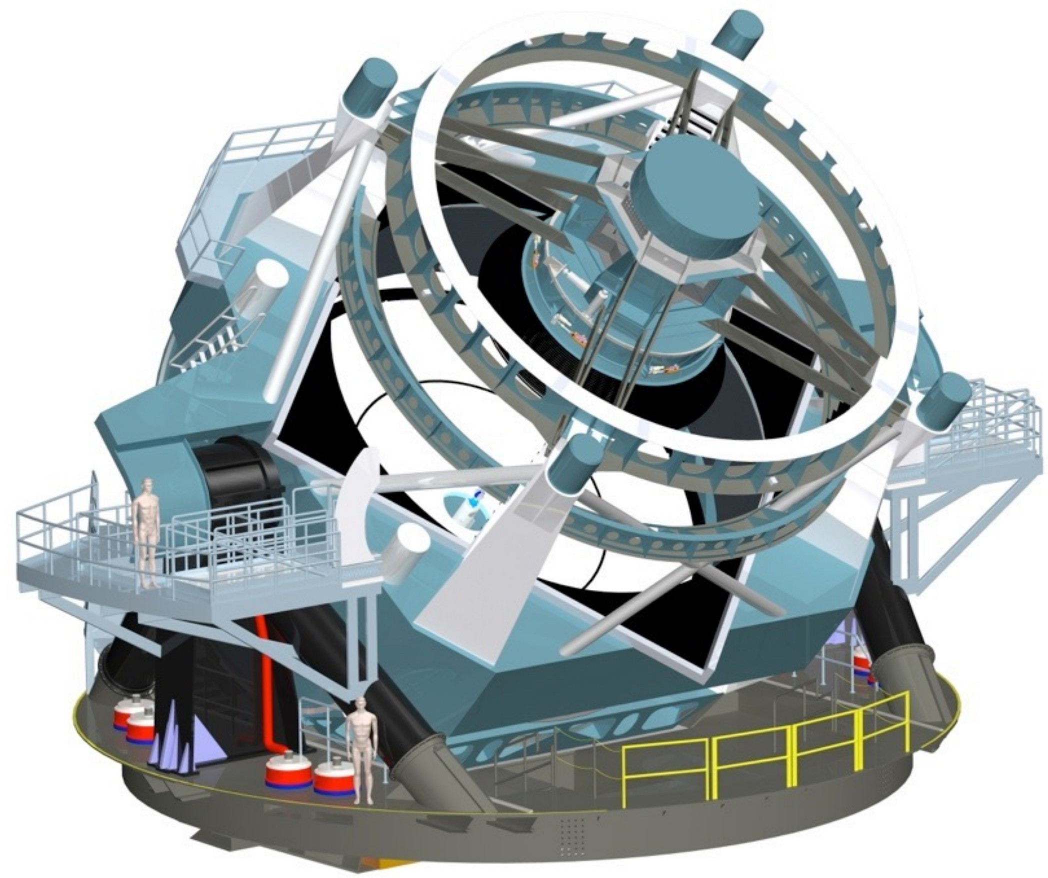
Wavefront PSF model:

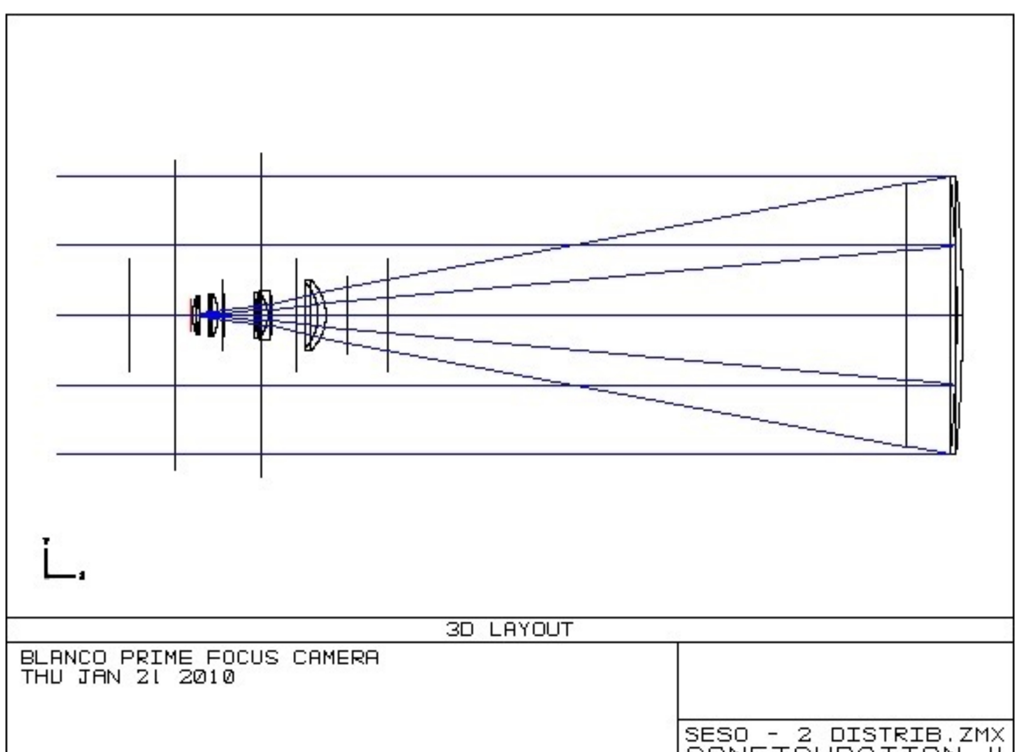
- measure optical wavefront at all Focal Plane locations
- parametrize image to image changes in wavefront in terms of a few physically motivated parameters
- fit Star's FWHM and Ellipticity to Wavefront PSF model

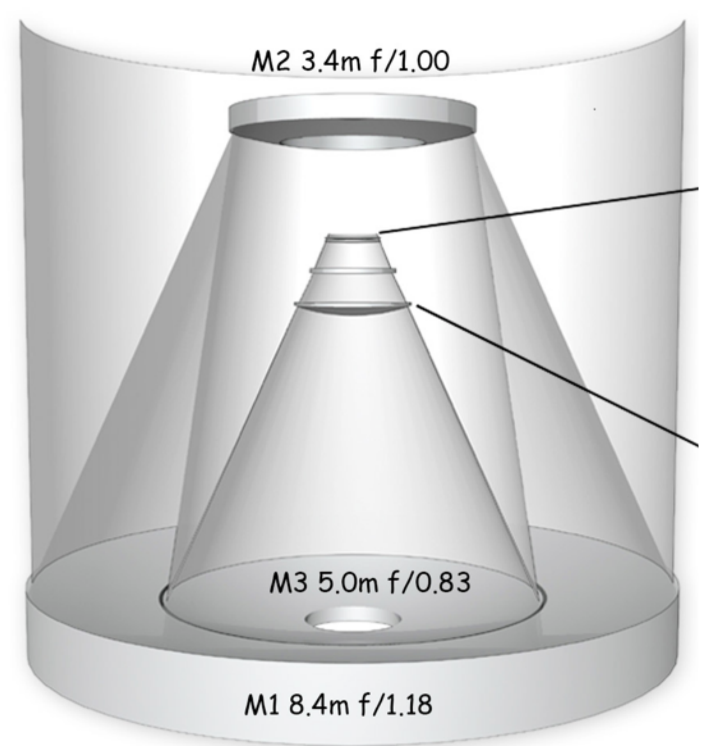
work by Chris Davis

Optical Systems: DECam + Blanco compared to LSST









DECam + Blanco: Optical Degrees of Freedom

Mirror Figure: Zernike polynomial
only Focus,Astigmatism,Coma,
Trefoil, Spherical needed

all Focal Plane points sample Primary Mirror Figure: *prime focus*

DECam Alignment only affects:
Focus, Astigmatism, Coma

$$W[x,y](\rho,\theta) = \sum_i a_i[x,y] Z_i(\rho,\theta)$$

$$a_i[x,y] = a_i(\mathrm{Ref.})[x,y] + \Delta_i + \Theta_i^x * y + \Theta_i^y * x$$

LSST will be more complicated

DES Donut Fitting Algorithm

- Model Wavefront at the pupil plane as a sum of Zernike terms

$$W(u,v) = \sum_{i=2}^{10} a_i Z_i(\rho,\theta)$$

- Calculate Donut image via Fraunhofer Diffraction

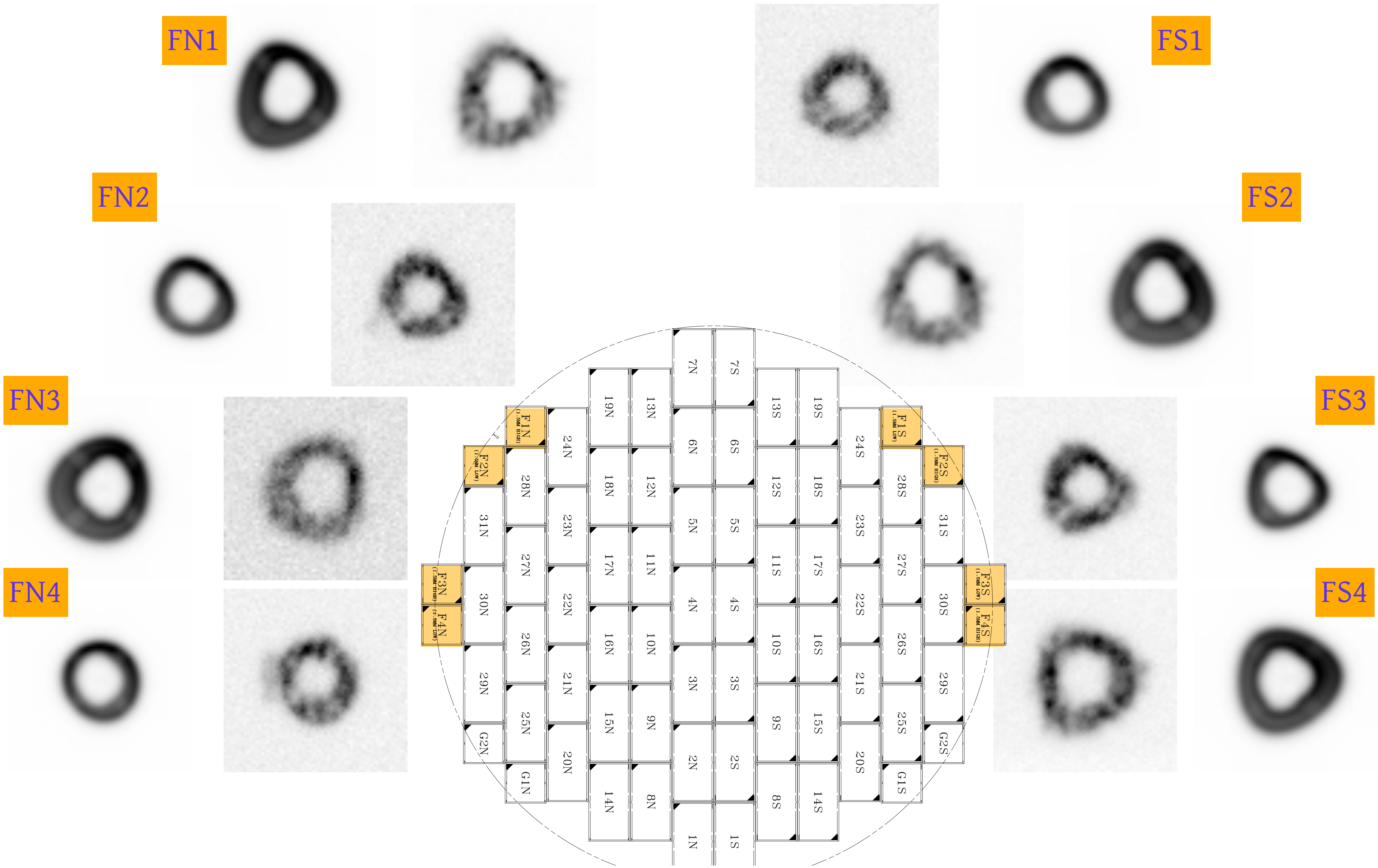
$$PSF(x,y) \sim \left| \mathcal{F}\left\{ P(u,v) e^{i\frac{2\pi}{\lambda}W(u,v)} \right\} \right|^2$$

- Convolute with smearing for Seeing, Pixelate.

$$I(x,y) \sim PSF \otimes Atmos \otimes Pixel$$

- Fit to find a_i
  - Non-linear χ^2 fit (MINUIT) to determine Zernike coefficients
    - Fit to 10 Zernike terms (or up to 15 Zernike Terms)
    - Fix or Float Seeing kernel
- Algorithm based on work of Fienup 1982,1993; Heathcote, Tokovinin 2006
- Fast algorithm, less than 2cpu sec/donut for 10 Zernike terms

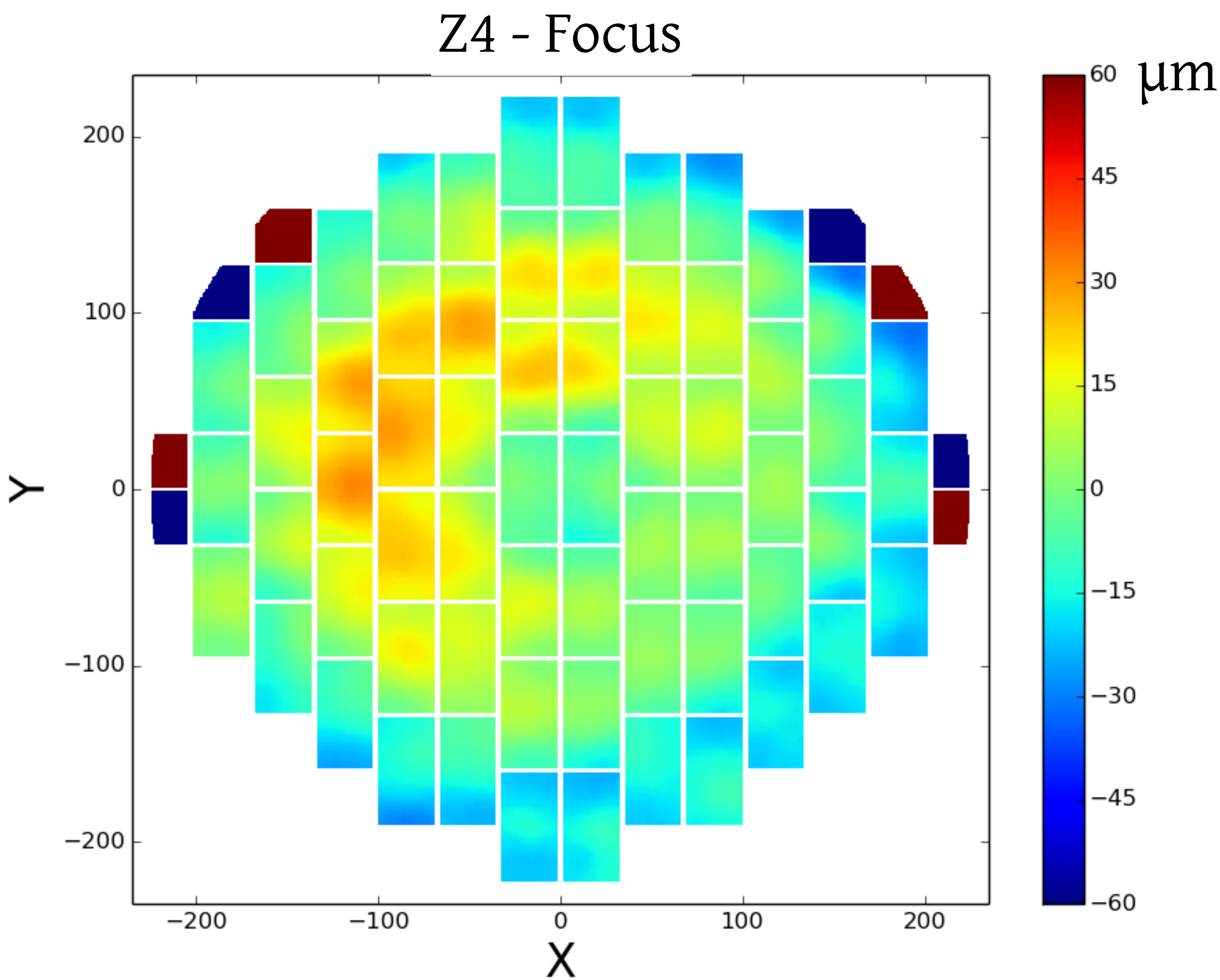
DECam Wavefront Sensors



- 8 2K x 2K CCDs, placed ±1.5mm out-of-focus
- read-out along with Science CCDs

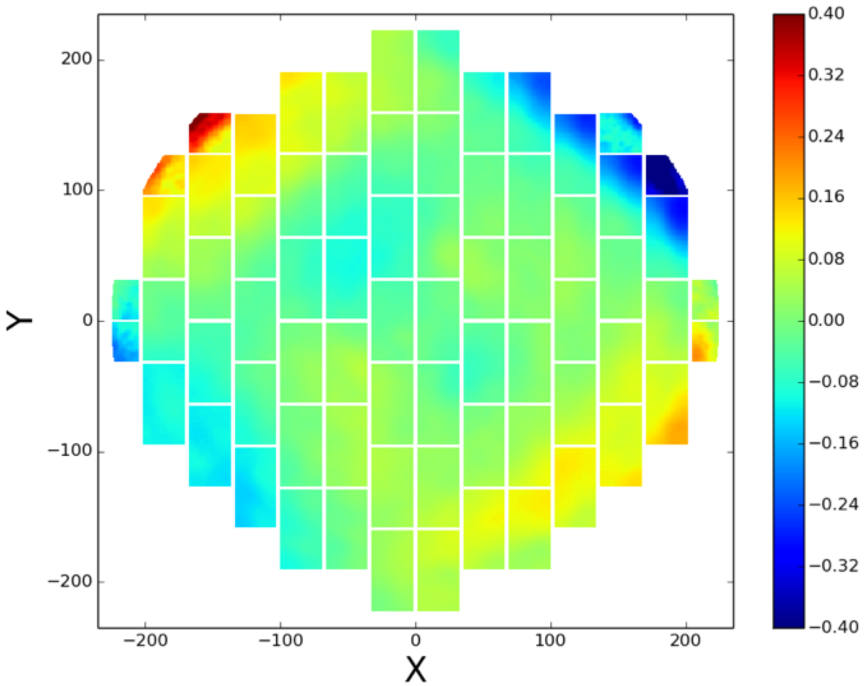
Reference Wavefront

Measure Reference Wavefront via out-of-focus stars

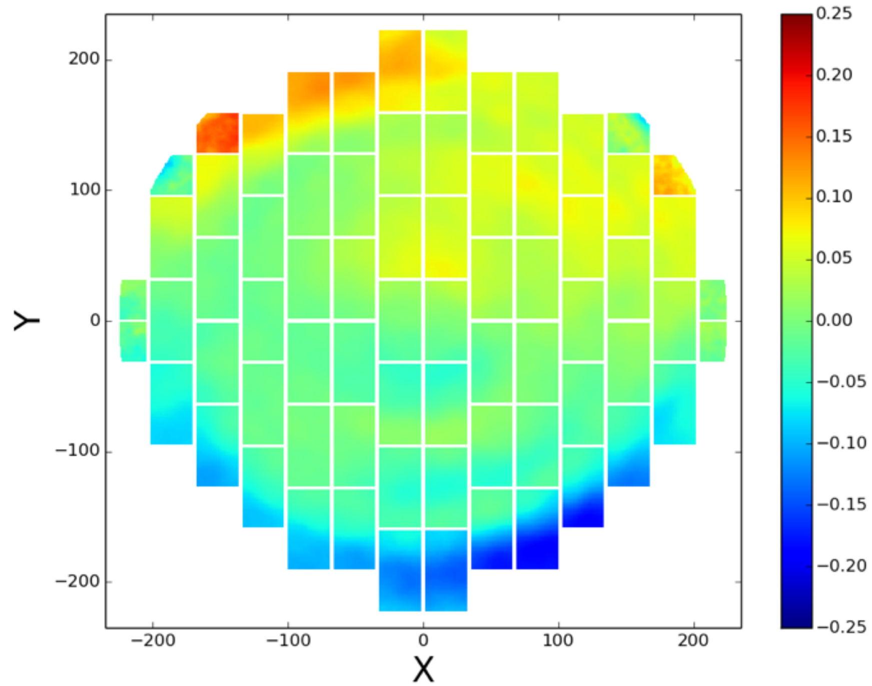


Reference Wavefront

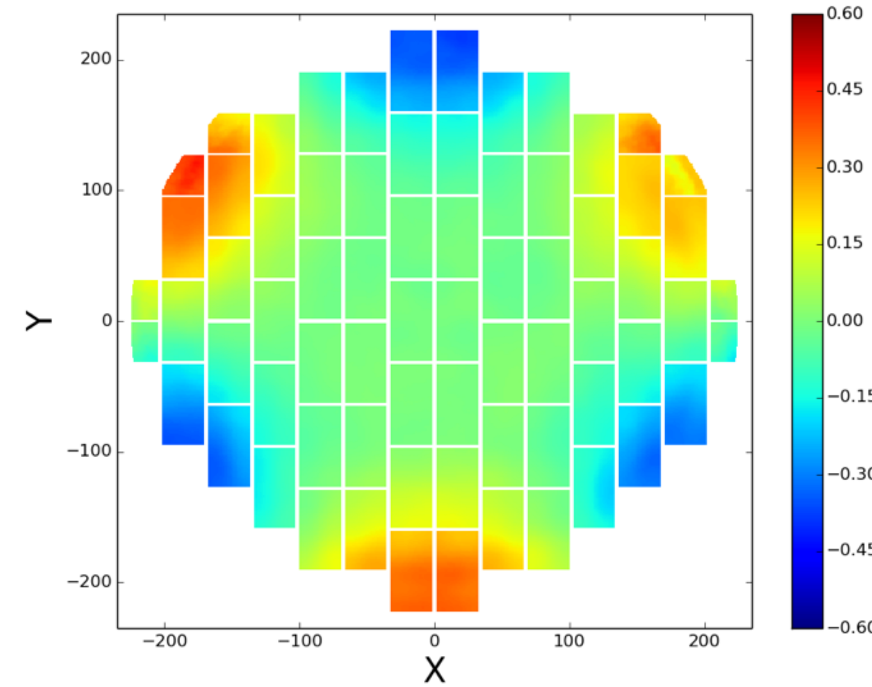
Z5 AstigmatismY



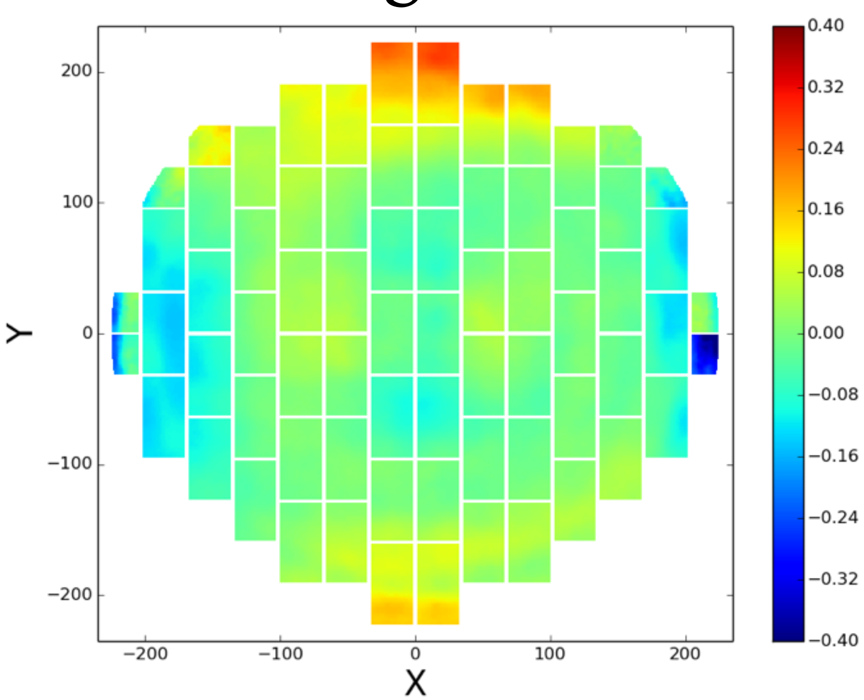
Z7 ComaY



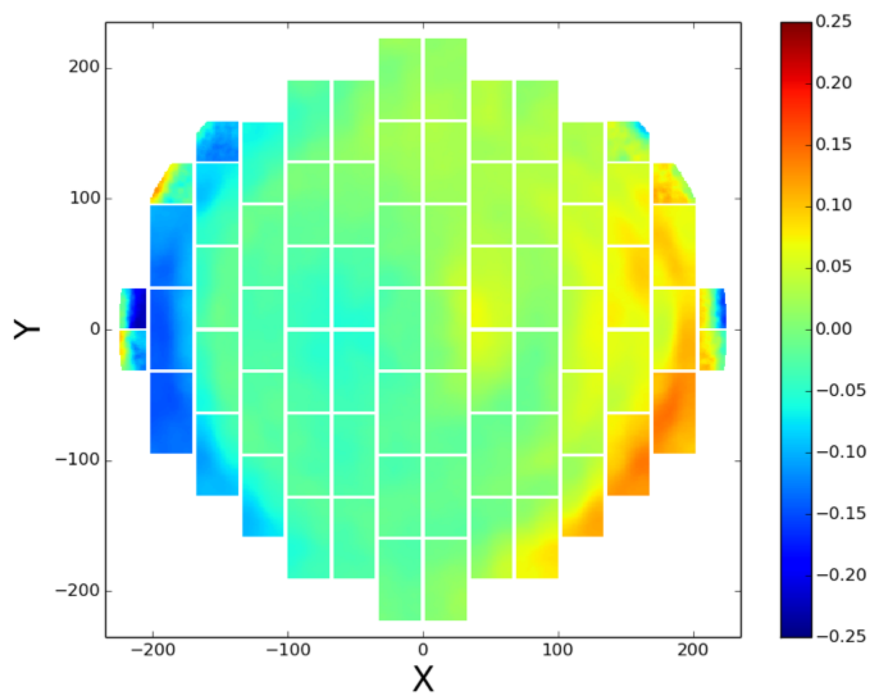
Z9 Trefoil Y



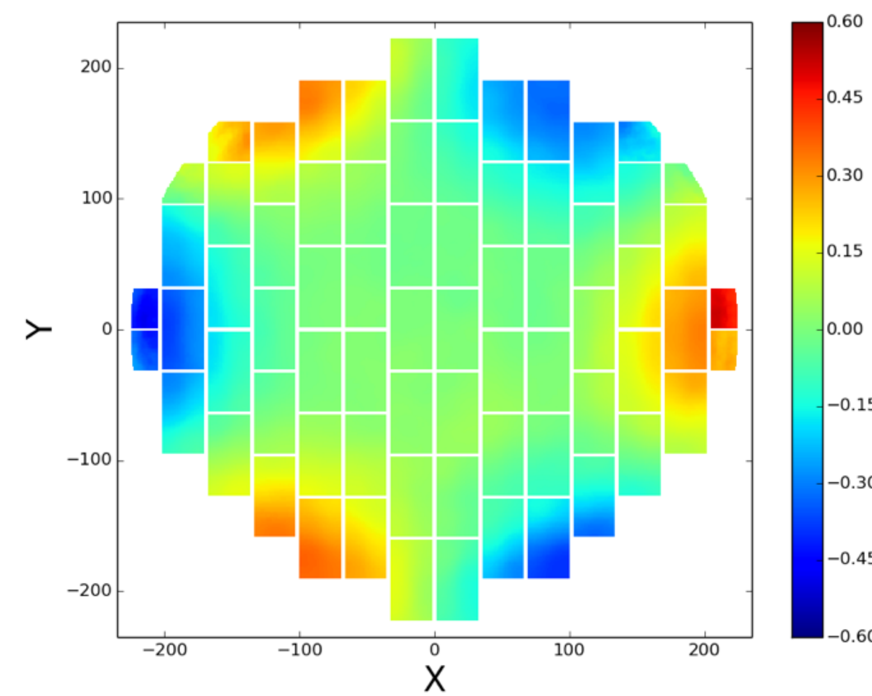
Z6 AstigmatismX



Z8 ComaX



Z9 Trefoil X



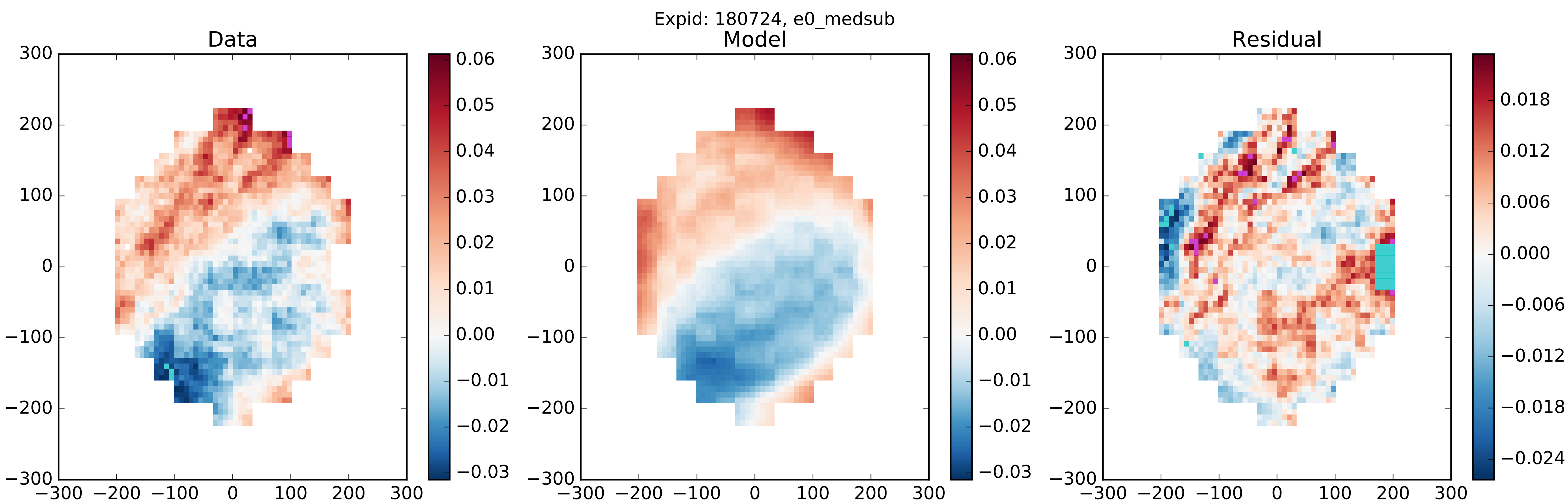
units are λ @(700nm)

Wavefront PSF Model Results

Fit DES SV images to Wavefront PSF Model
see Chris's poster for details

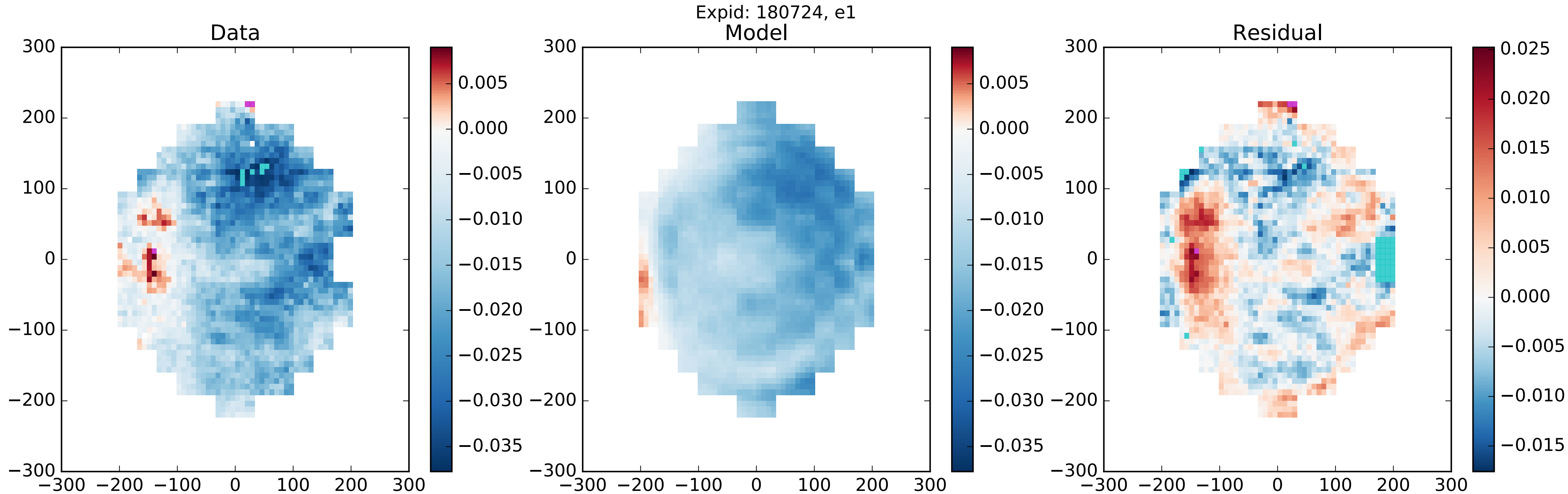
compare e0 Data, Model, and Data-Model

$$e0 = I_{xx} + I_{yy}$$

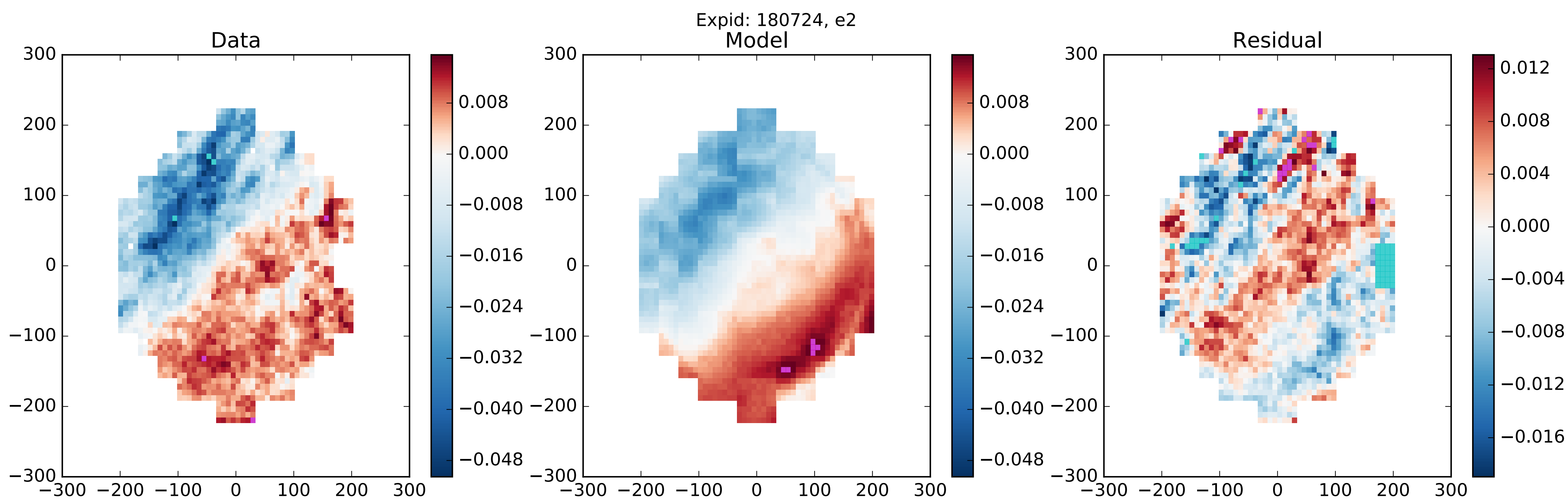


Wavefront PSF Model Results

$$e1 = I_{xx} - I_{yy}$$

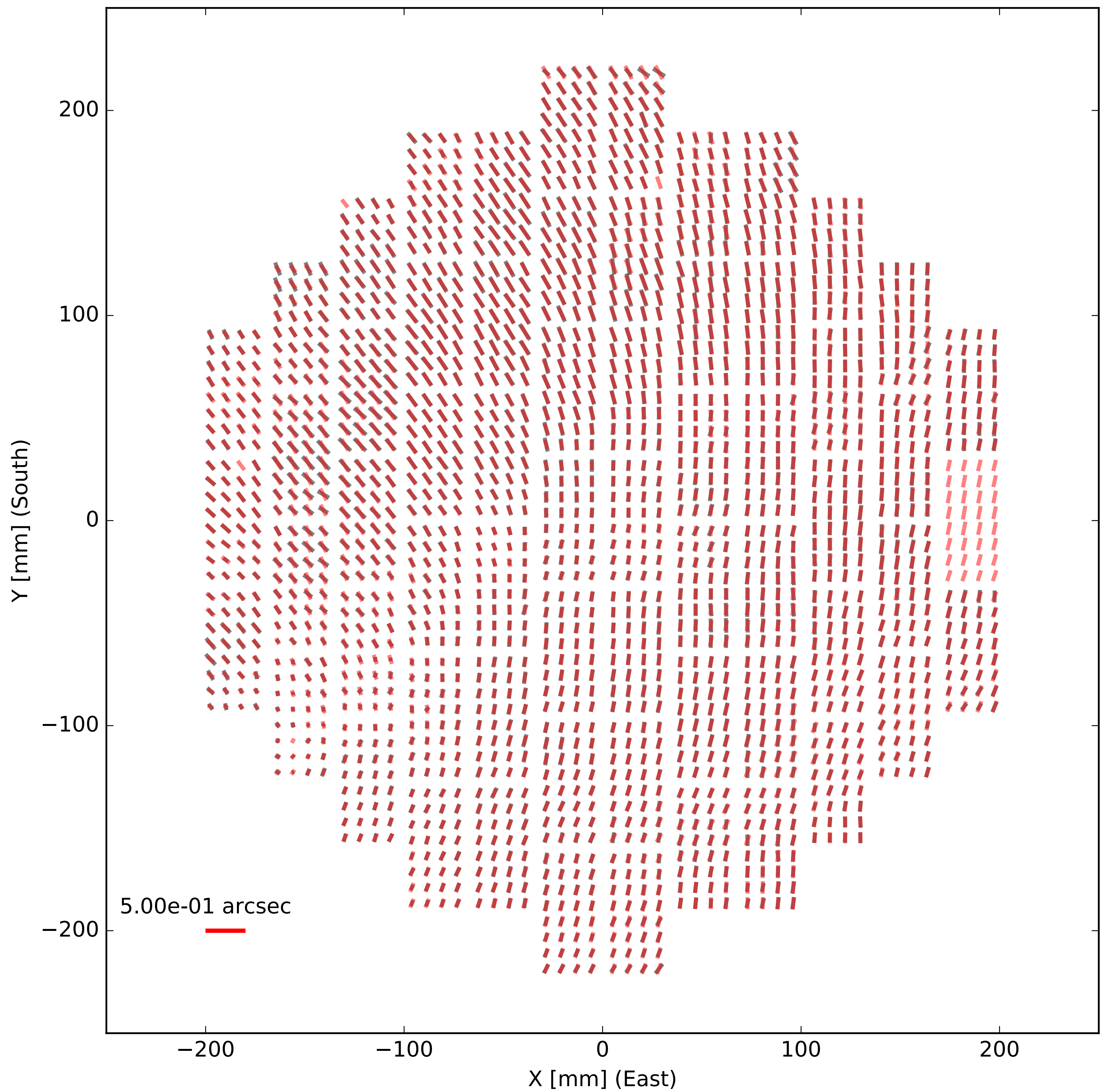


$$e2 = 2I_{xy}$$



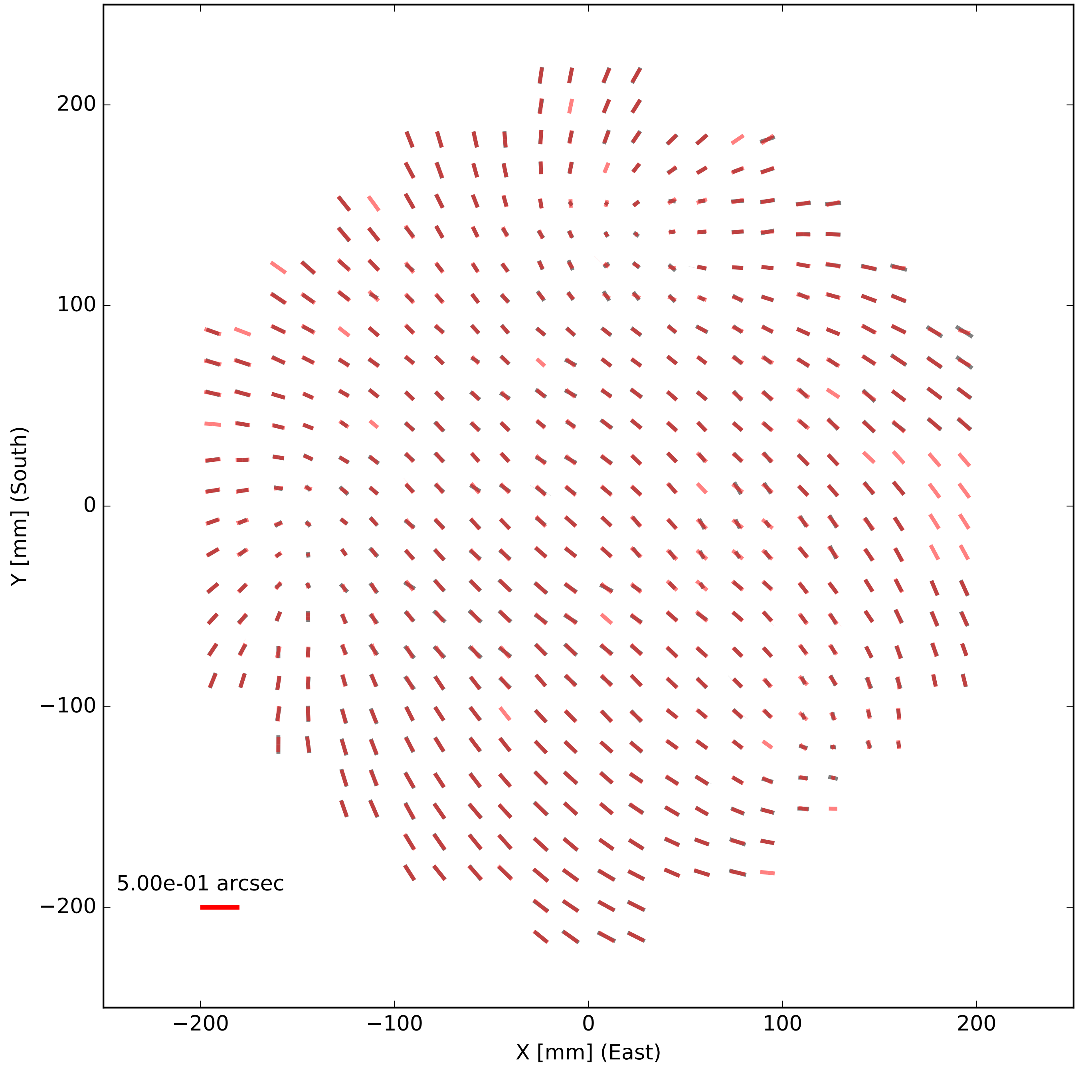
Wavefront PSF Model Results

$$w = \left[(I_{xx} - I_{yy})^2 + (2I_{xy})^2 \right]^{1/4}$$

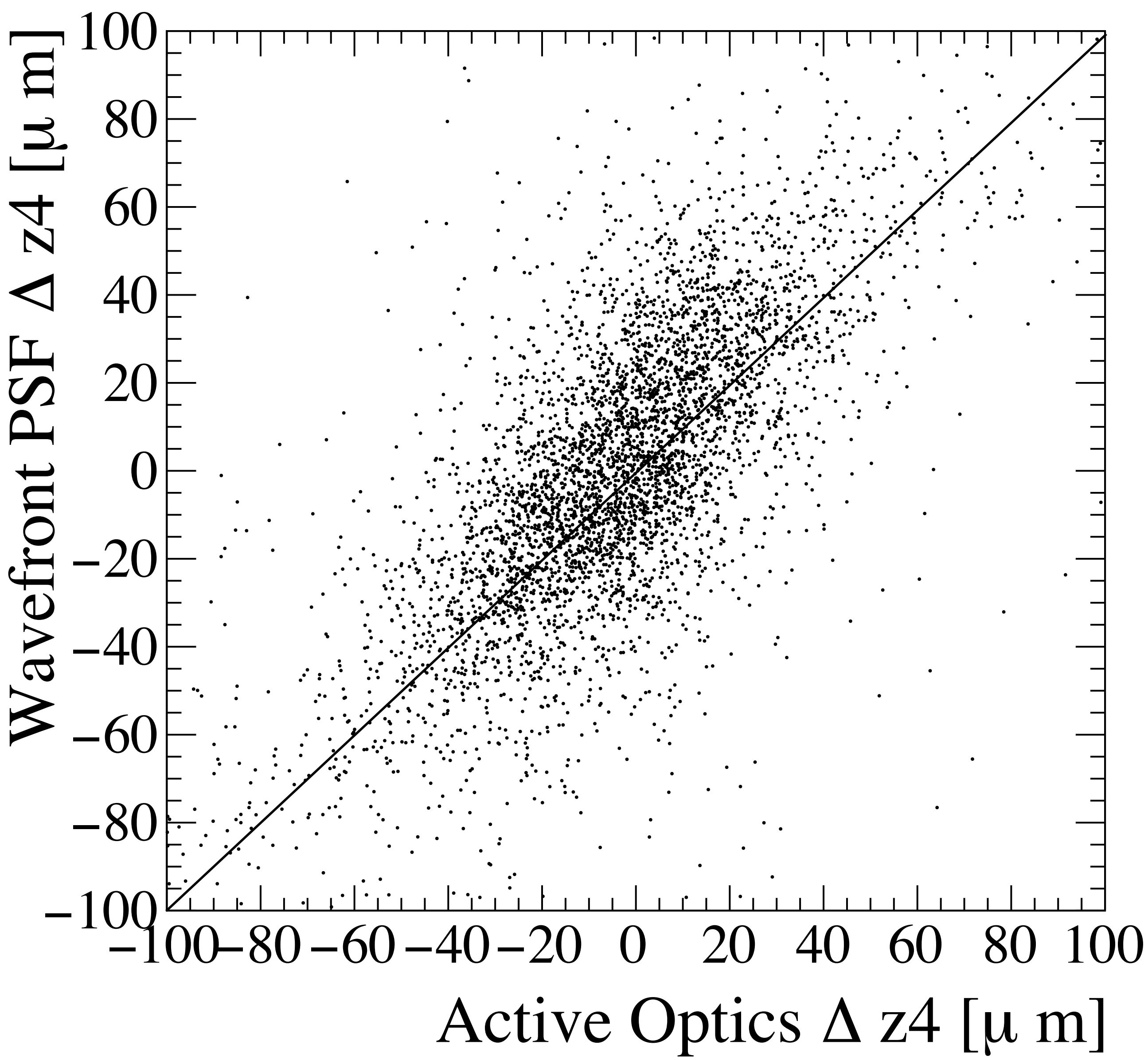


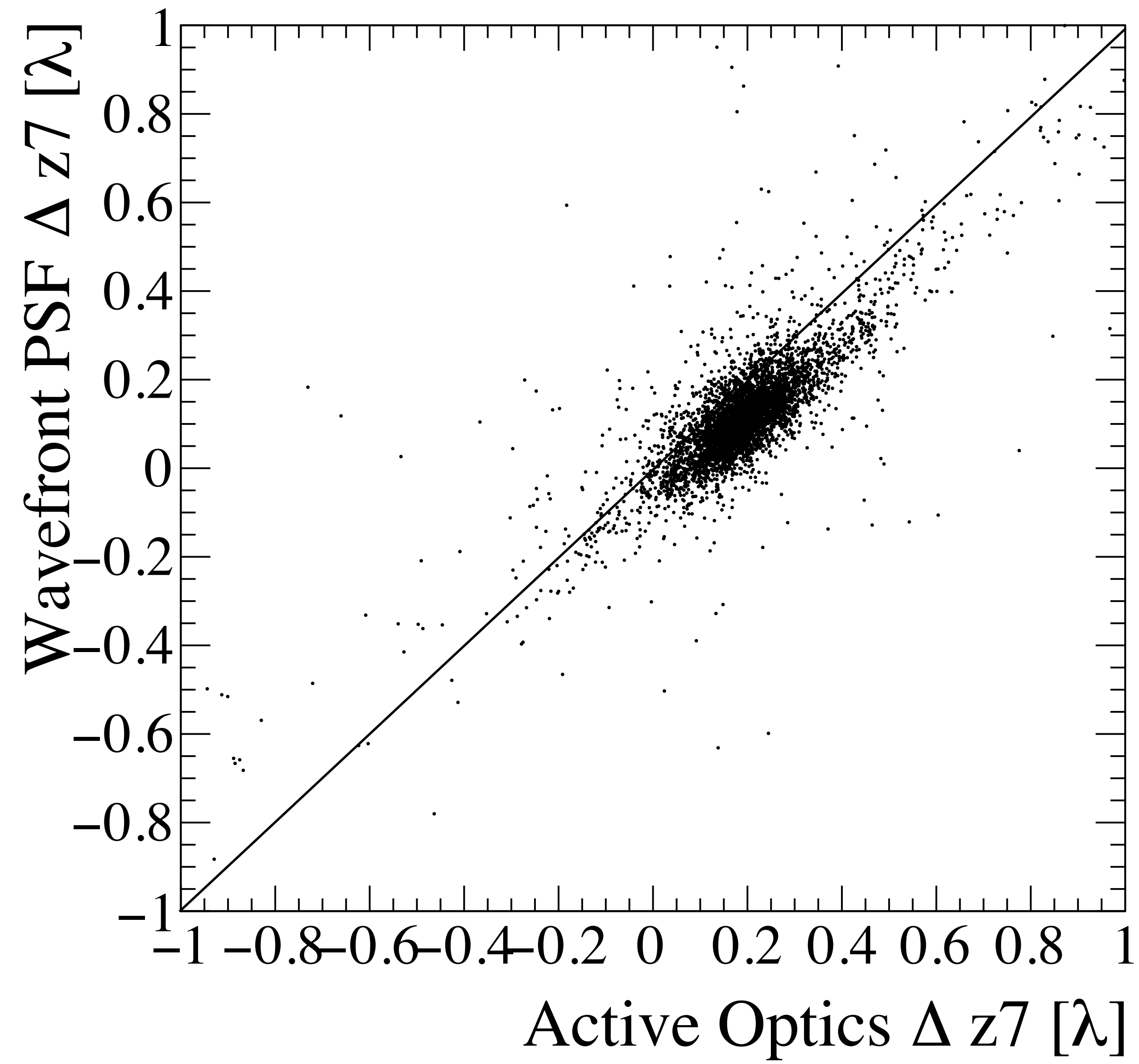
Wavefront PSF Model Results

prior to Hexapod under Active control



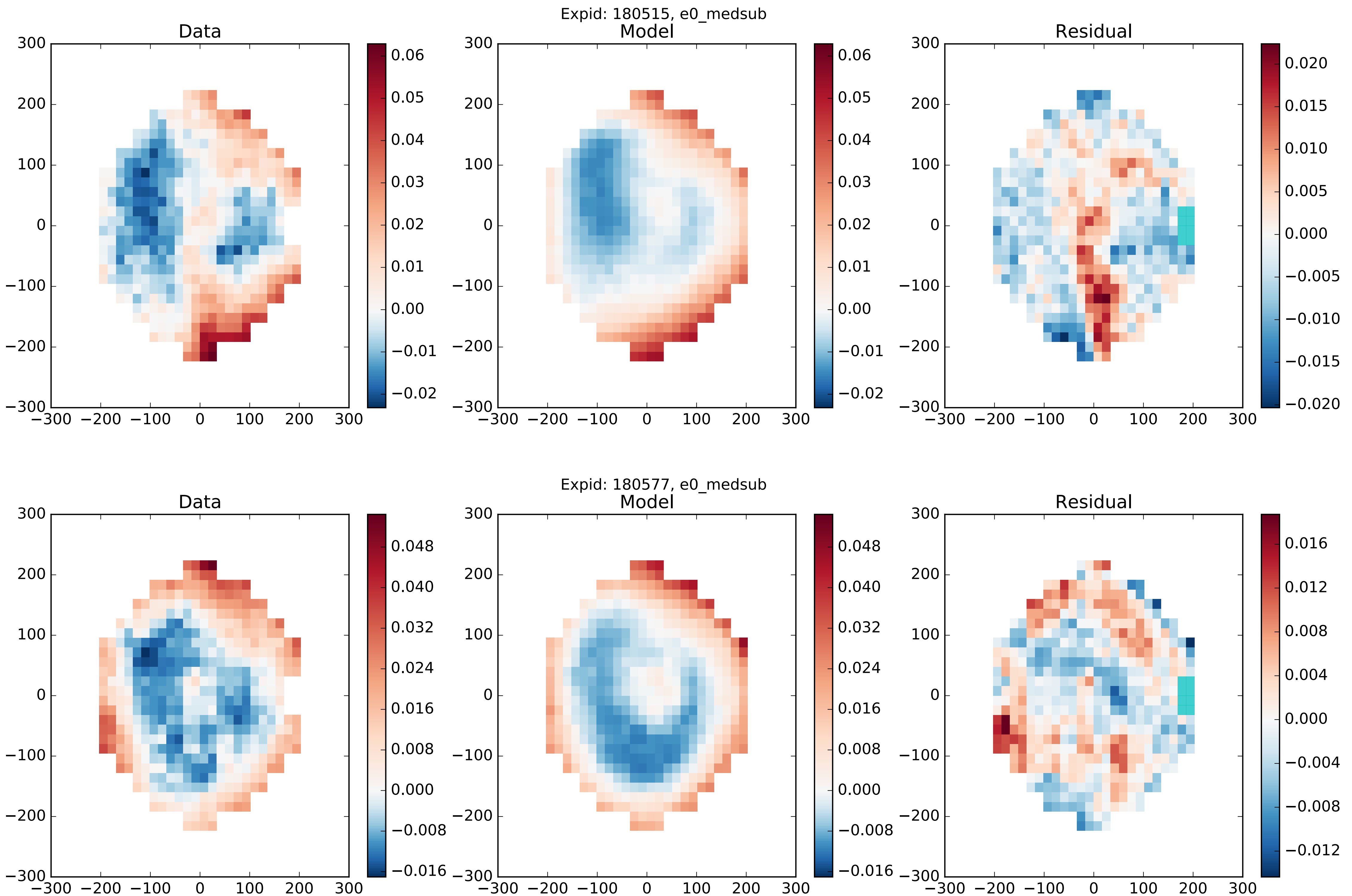
Compare Active Optics System vs. Wavefront PSF Model



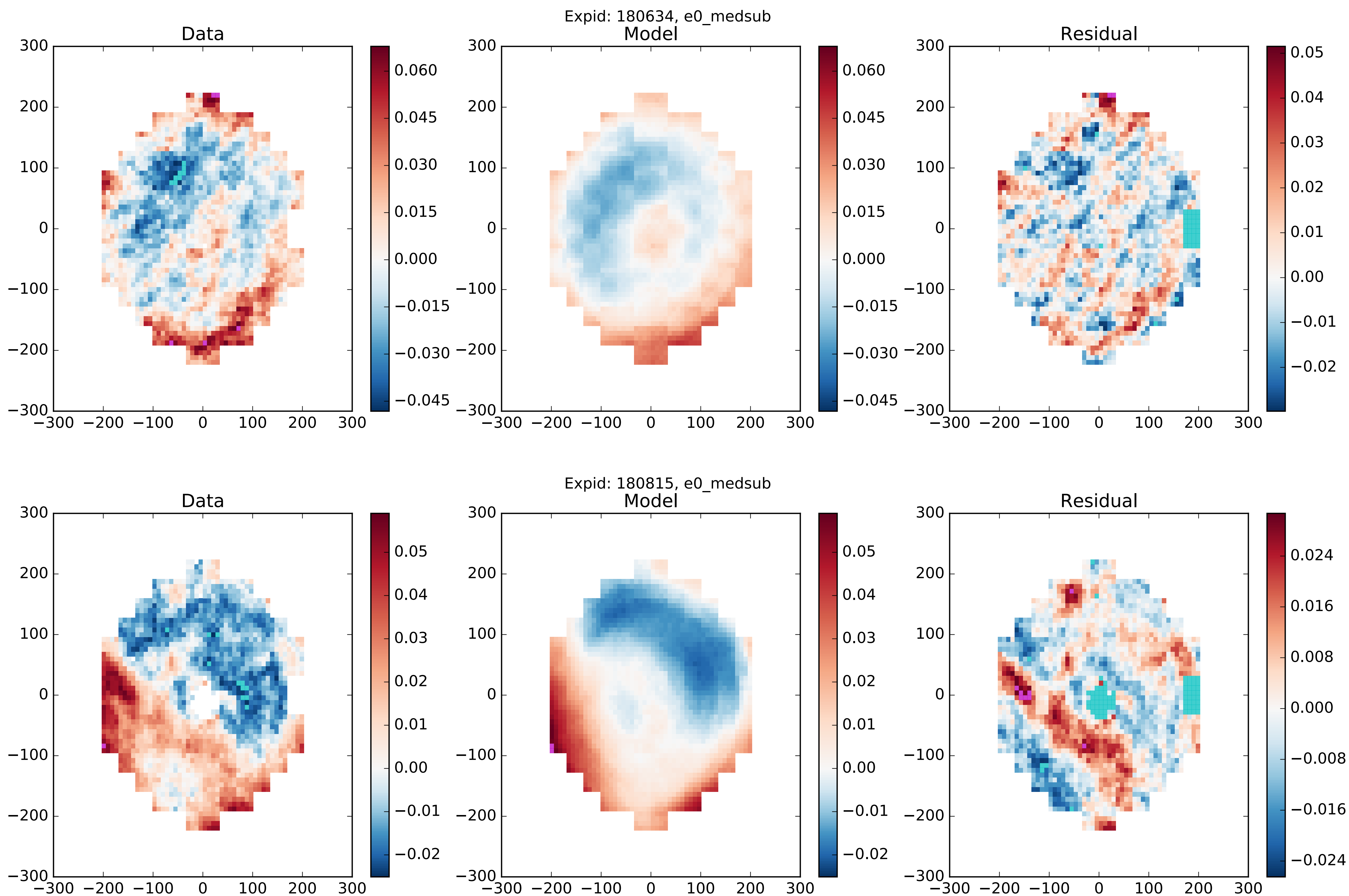


AOS uses Wavefront CCDs (out of focus) to determine Focus & Hexapod alignment in real time

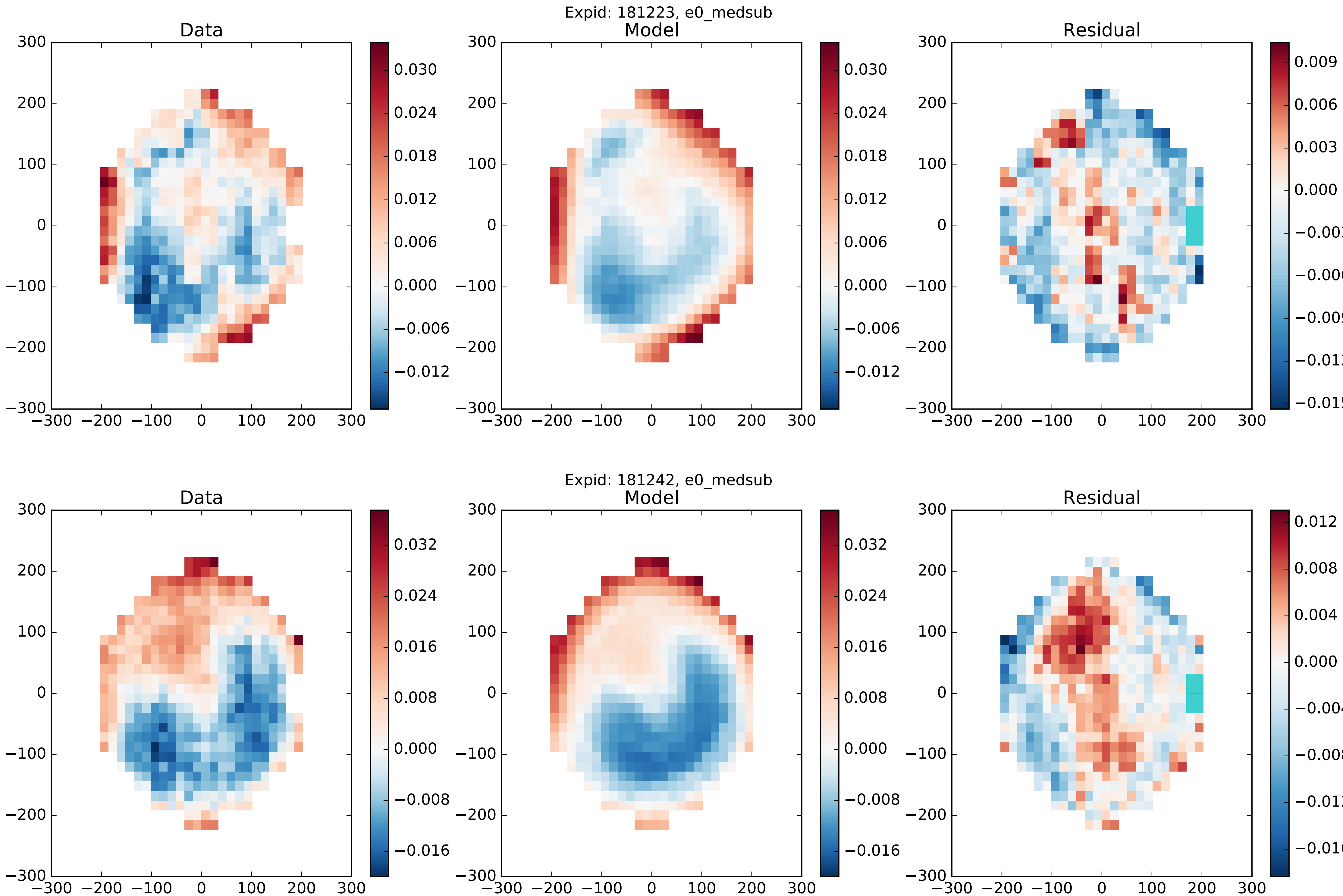
Wavefront PSF Model Results - more images



Wavefront PSF Model Results - more images



Wavefront PSF Model Results - more images



Atmospheric Contribution to Wavefront & PSF

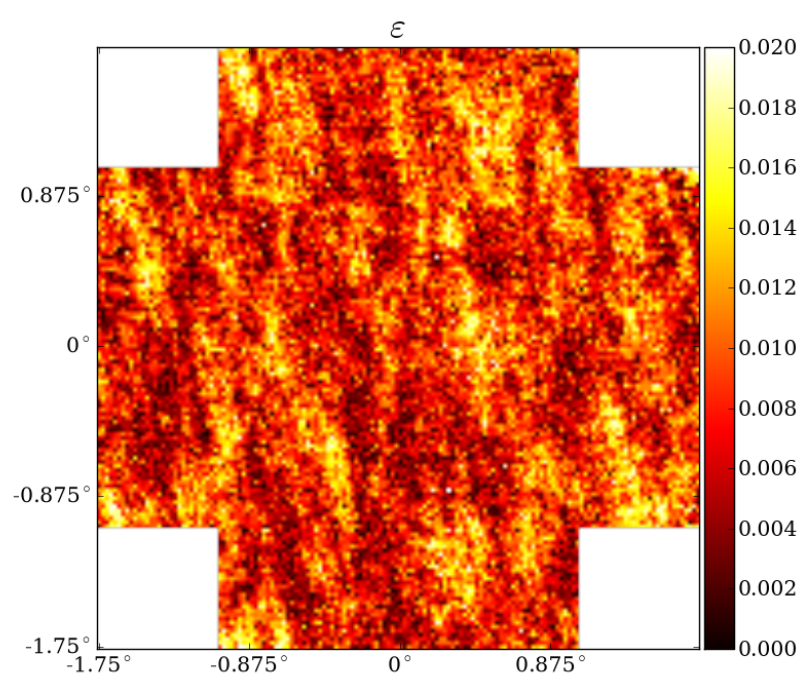
Wavefront PSF Model:

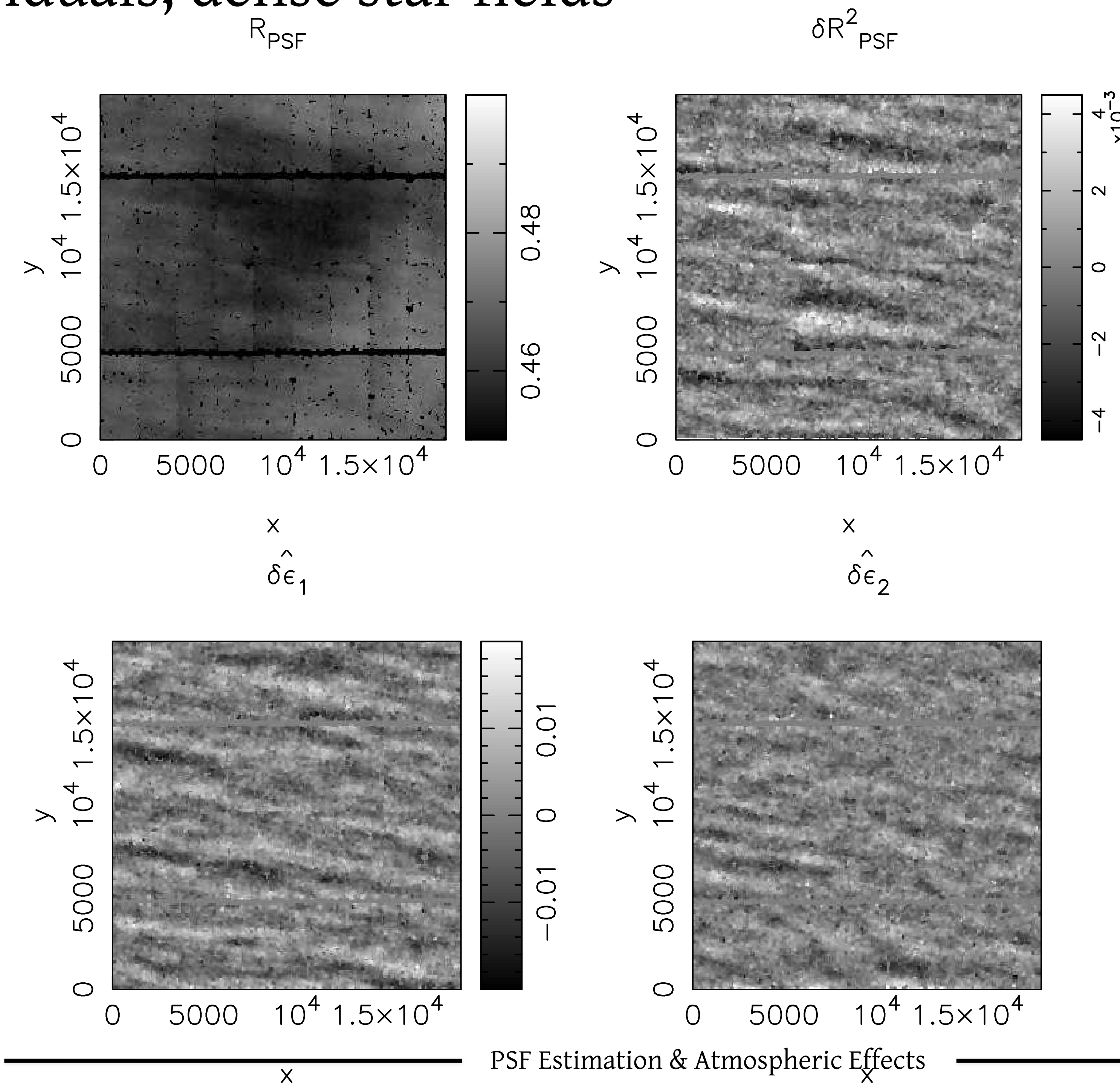
- only includes optical Wavefront
- seeing included with a Kolmogorov kernel, assumed to be uniform over Focal Plane
- also include a uniform jitter contribution

- Seeing variations over the Focal Plane not included
- Interpret Residuals as due to Seeing
- Structure of Residuals is suggestive of Correlations in the Atmospheric Turbulence pattern

Literature on Wide-Field Seeing Correlations

- LSST simulations (C. Chang etal, 2012)
- CFHT data (C. Hymans etal, 2011)
  - 74sec exposure
  - high spatial order residuals, dense star fields



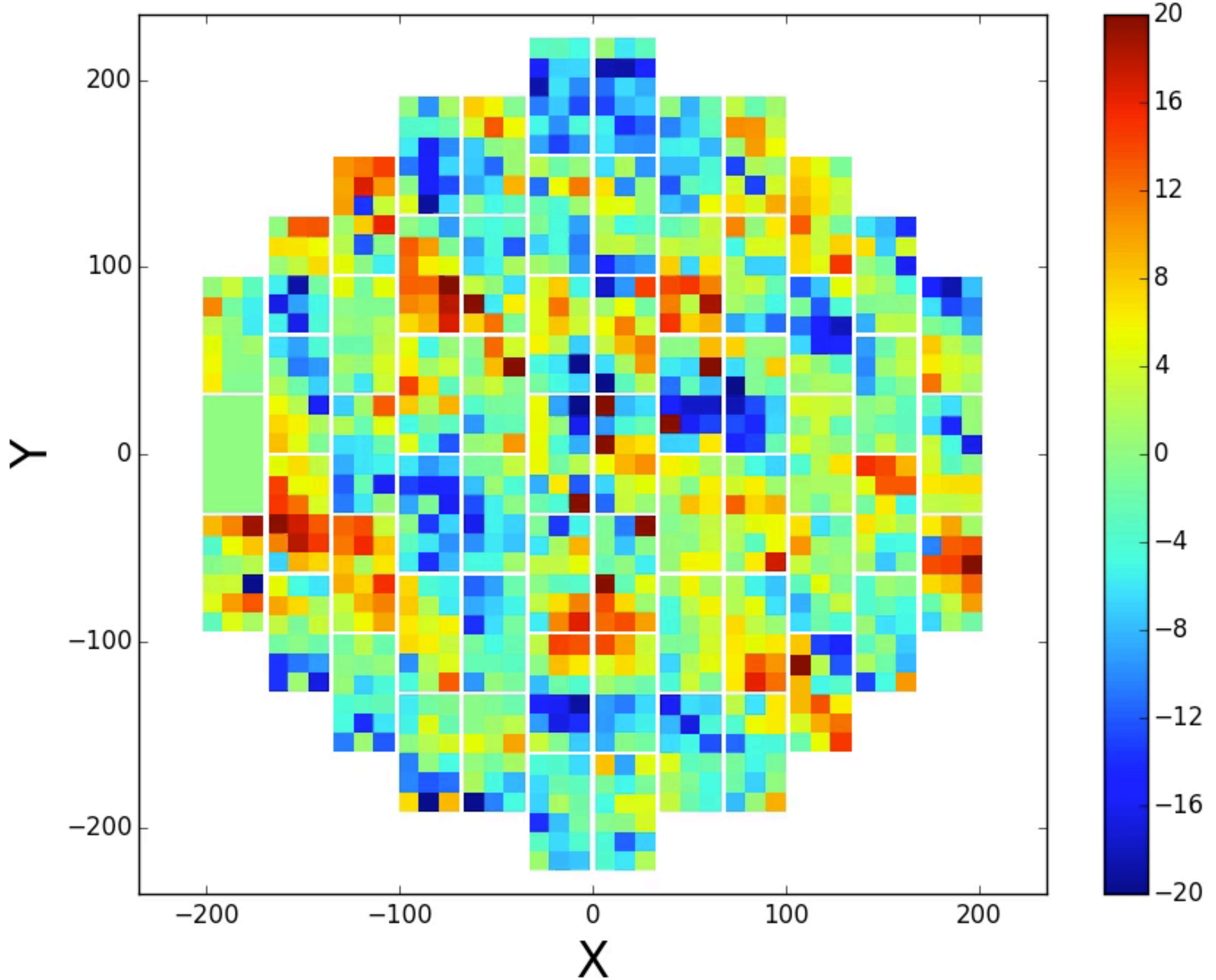


Wavefront Temporal Variations

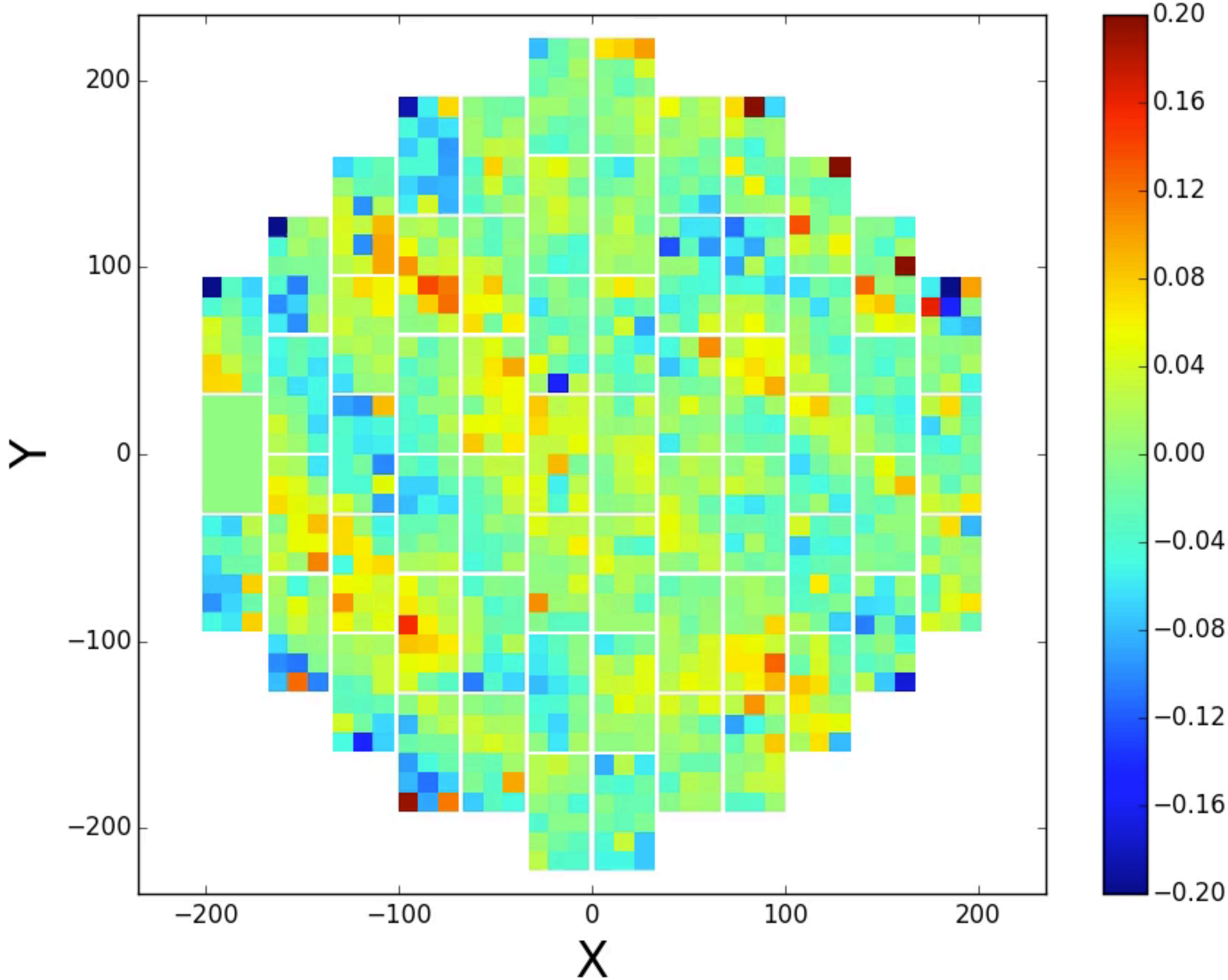
- Sequence of 98 30-second i-band out-of-focus dithered images
- Donuts analyzed in usual way
- Combine Donuts from all images to form a Reference Wavefront
  - Each Zernike term adjusted by Δ, θx, θy in individual images to allow for Hexapod or Primary Mirror drifts
- Next plot the difference between the combined Wavefront and each image's Wavefront
- see the movies

$$\Delta a_i(\mathrm{Image}_j)[x,y] = a_i(\mathrm{Image}_j)[x,y] - a_i(\mathrm{Ref.})[x,y]$$

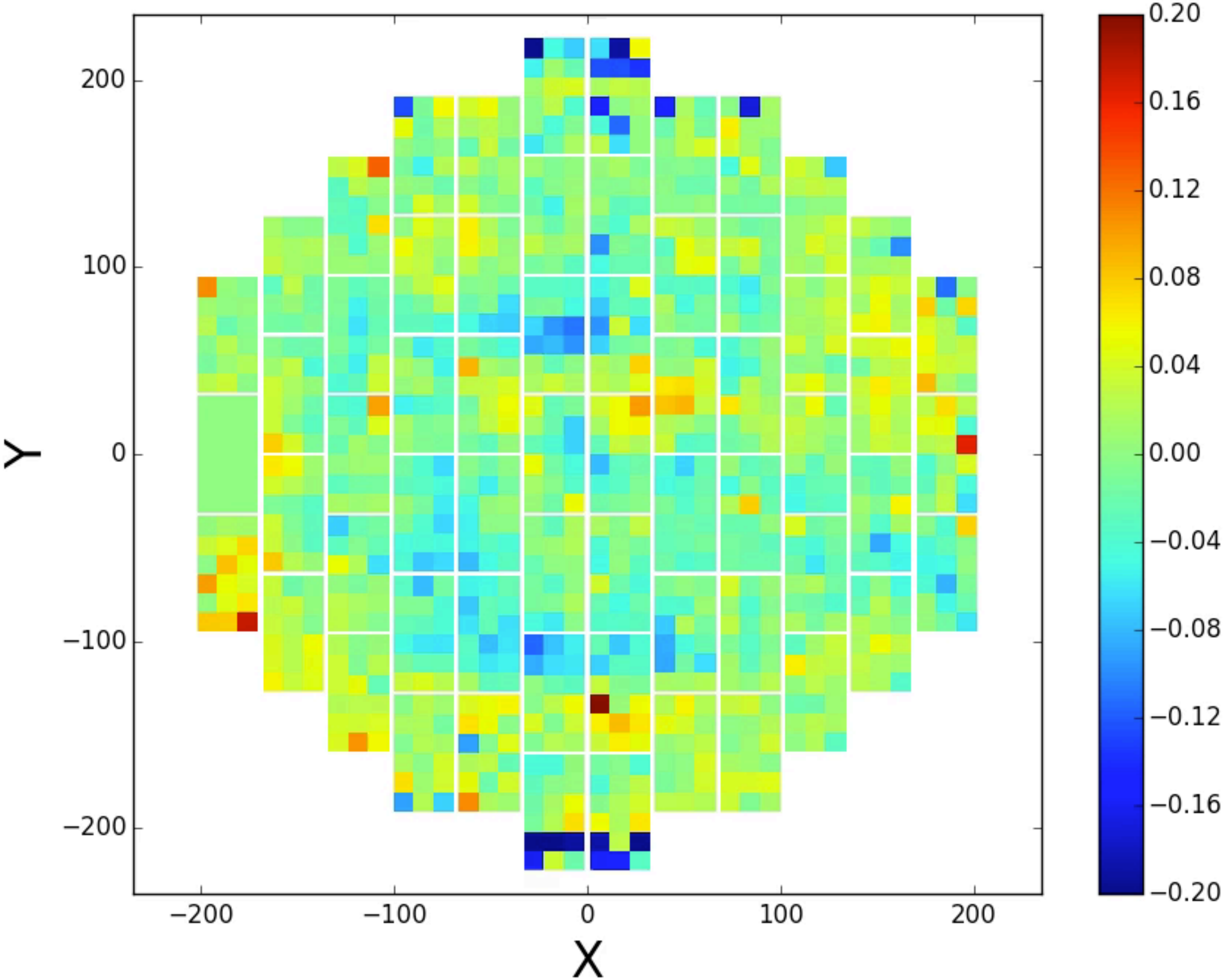
Changes in Focus Zernike



Changes in Astigmatism Y Zernike

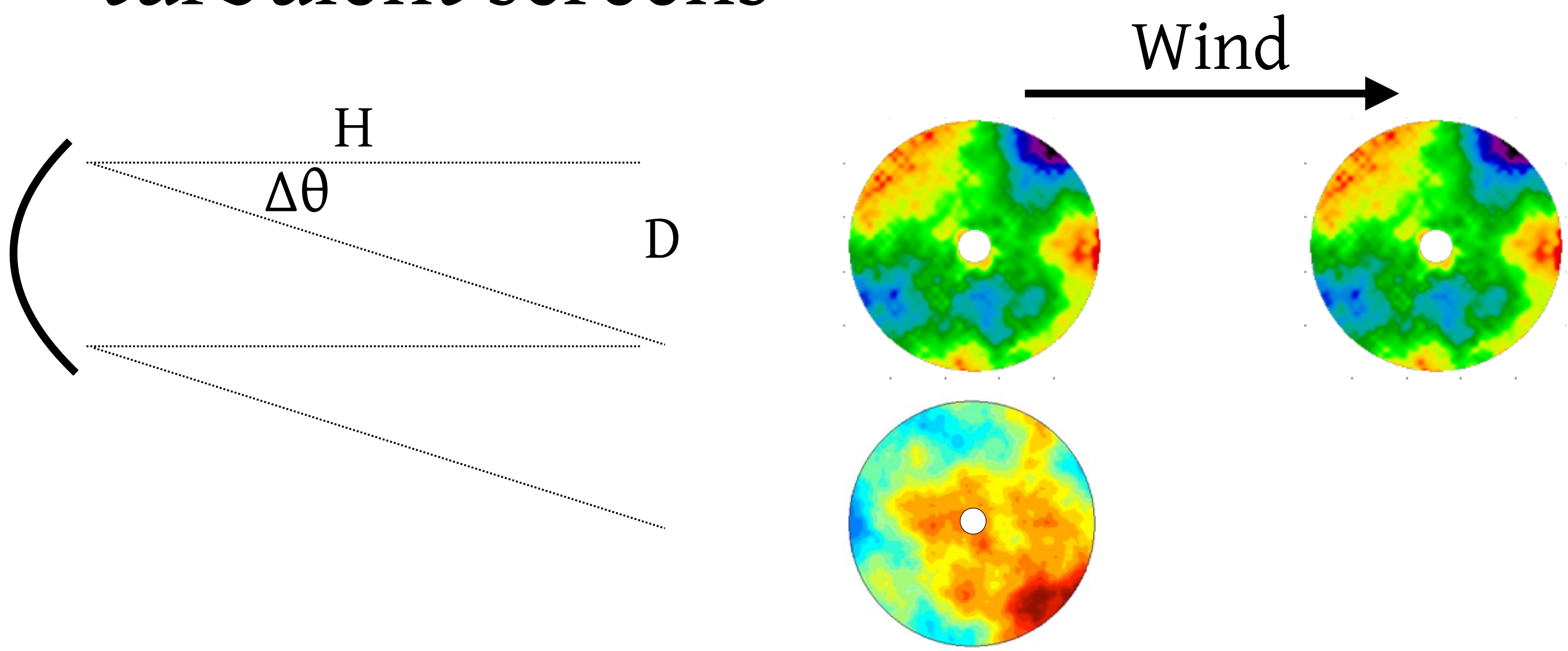


Changes in Astigmatism X



Atmospheric Turbulence Correlations

- frozen flow of turbulent screen across pupil
  - separated points on Focal Plane view same turbulent screens



see Adam Snyder's poster

- Turbulent pattern is uncorrelated for $H > D/\Delta\theta$
  - ground layer turbulence affects Pupil uniformly across F.O.V., and hence also all of Focal Plane
  - coherence present on angular scale of $\Delta\theta \sim 0.2°$
  - corresponds to $H > 1100$ meters

Future Study

Temporal Wavefront Variations

- DECam data with 10 and 90 second exposures
- scaling between DES and LSST:
  - variance of wavefront ~ $(D/r_0)^{5/3}T$
- model corresponding PSF variations

Wavefront PSF Model

- DES Year 1 and 2 Data
- Study PSF residuals
- Develop PSF pipeline
  - deconvolve measured PSF and model PSF
  - use interpolation method for measured - model